US008269388B2

(12) **United States Patent**
Smithanik et al.

(10) **Patent No.: US 8,269,388 B2**
(45) **Date of Patent: Sep. 18, 2012**

(54) **MAGNETIC BEARING ASSEMBLY FOR ROTORS**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 747 days.

(21) Appl. No.: **12/322,424**

(22) Filed: **Feb. 2, 2009**

(65) **Prior Publication Data**

US 2010/0194224 A1 Aug. 5, 2010

(51) **Int. Cl.**
H02K 7/09 (2006.01)

(52) **U.S. Cl.** **310/90.5**

(58) **Field of Classification Search** .... 310/90.5, 310/68 B

See application file for complete search history.

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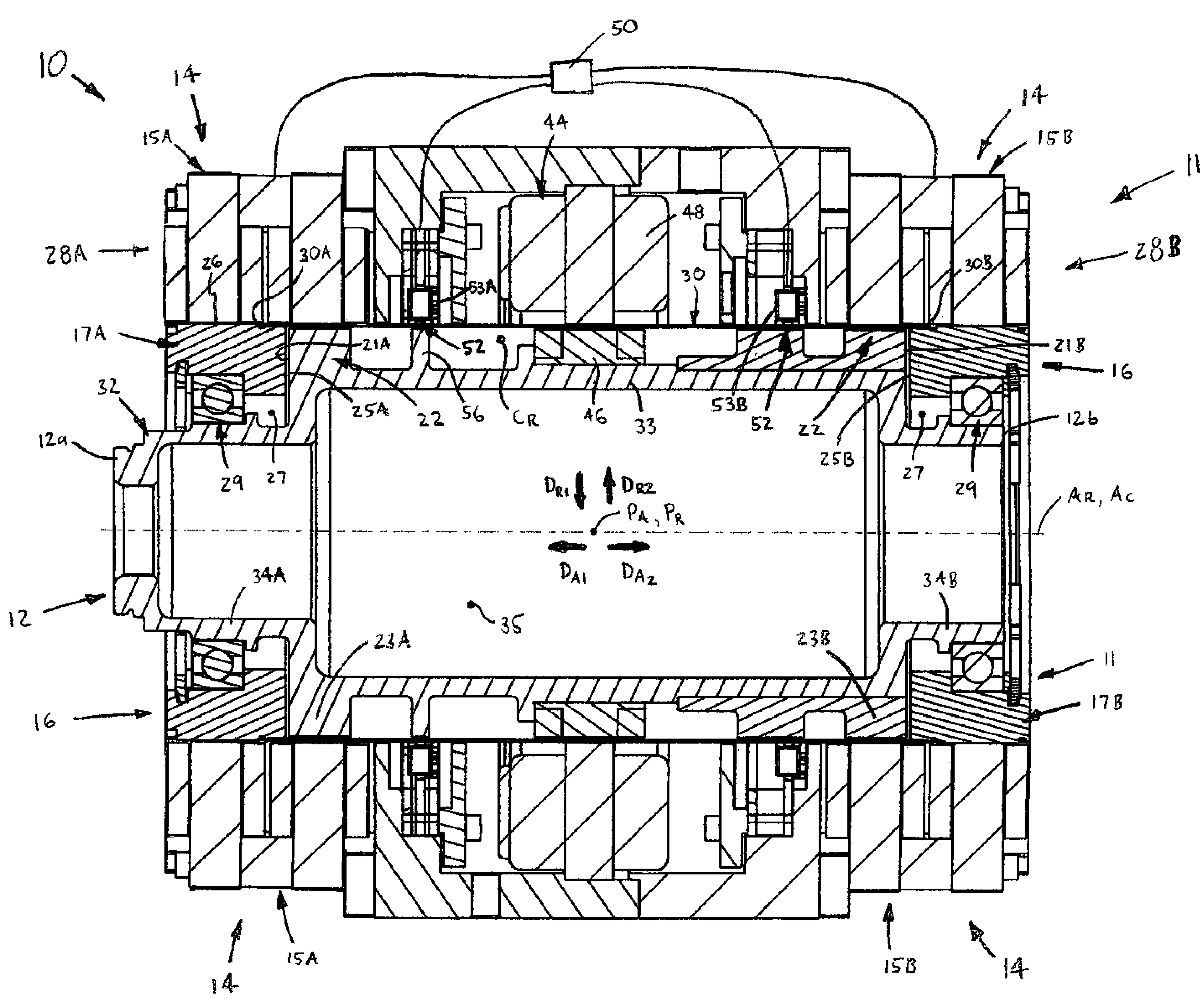
(57) **ABSTRACT**

A rotor assembly includes a rotor having a central axis extending between the two opposing ends and a radial surface, and is rotatable about the central axis. At least one electromagnet is disposed proximal to and configured to exert magnetic force on a portion of the rotor. Further, a channeling member is disposed generally adjacent to the electromagnet and has a radial surface disposed adjacent to the rotor radial surface. As such, magnetic flux generated by the electromagnet extends generally radially between the electromagnet and the rotor portion and generally axially between the rotor portion and the channeling member so that the magnetic force biases the rotor both radially and axially to maintain the rotor at a desired position. Preferably, the assembly includes a plurality of magnets proximal to each end, two channeling members, and a tubular body extending between the channeling members and enclosing the rotor.

25 Claims, 8 Drawing Sheets



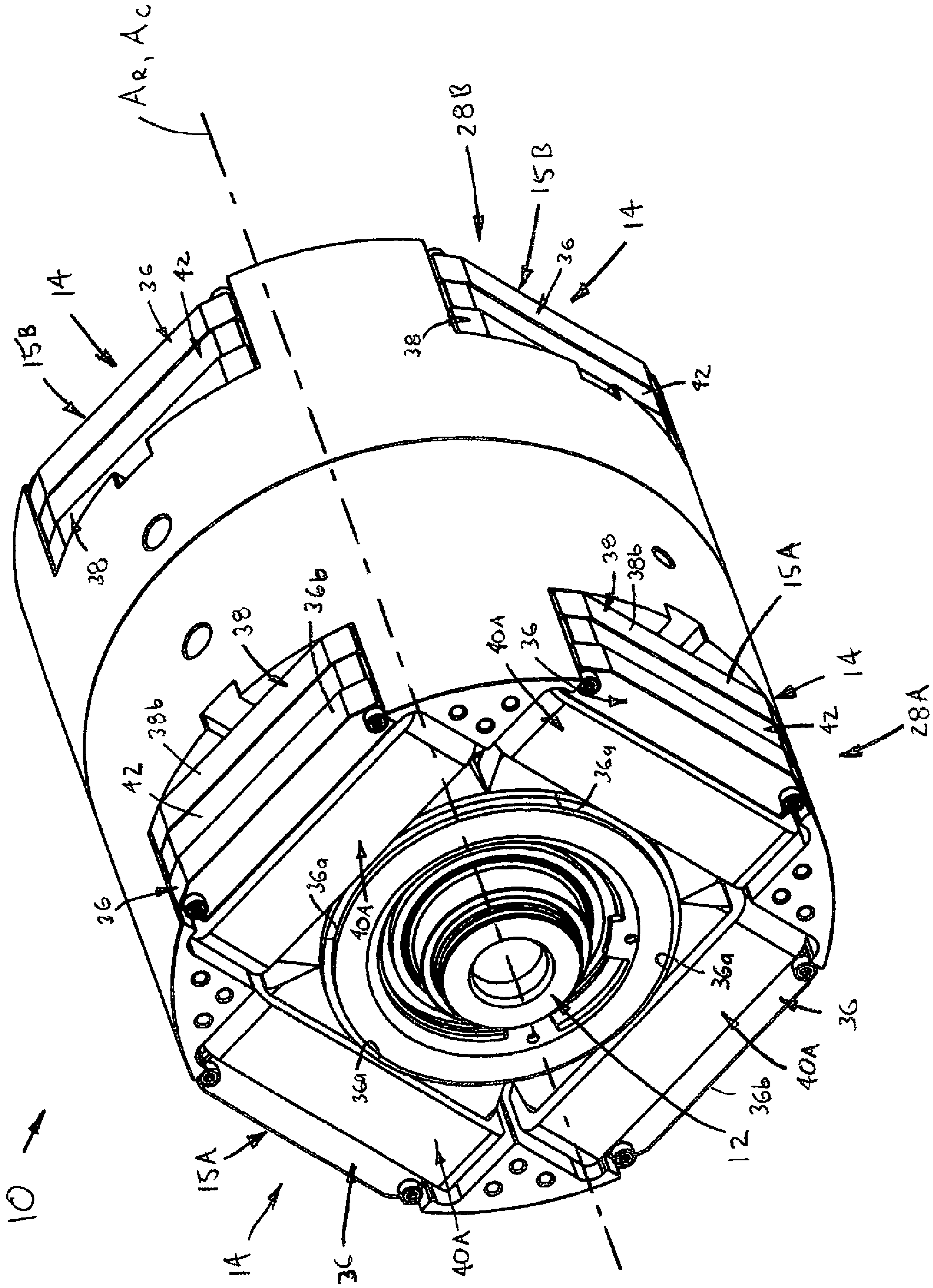
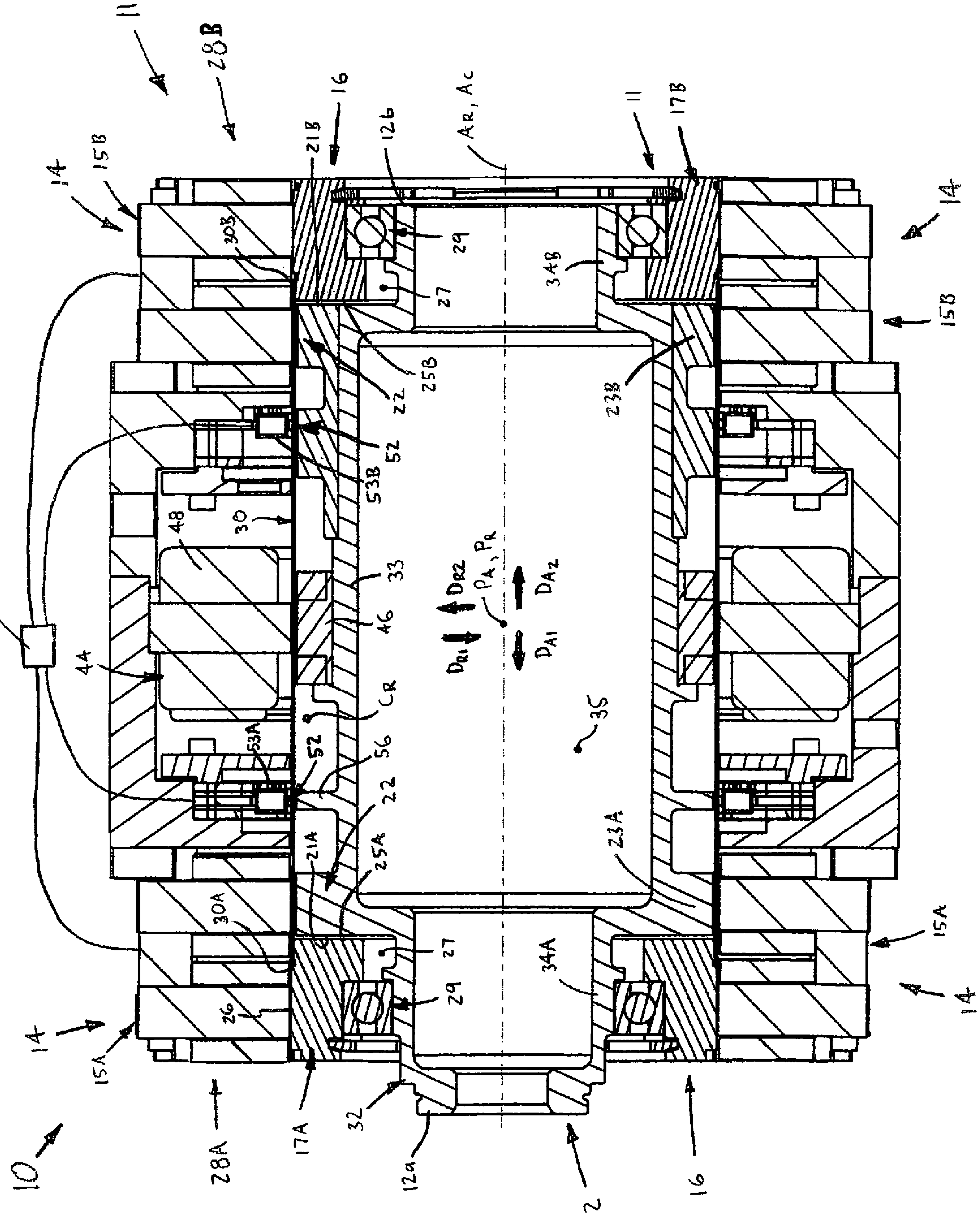


FIG. 1


10
11
12
12a
12b
14
15A
15B
16
17A
17B
21A
21B
22
23A
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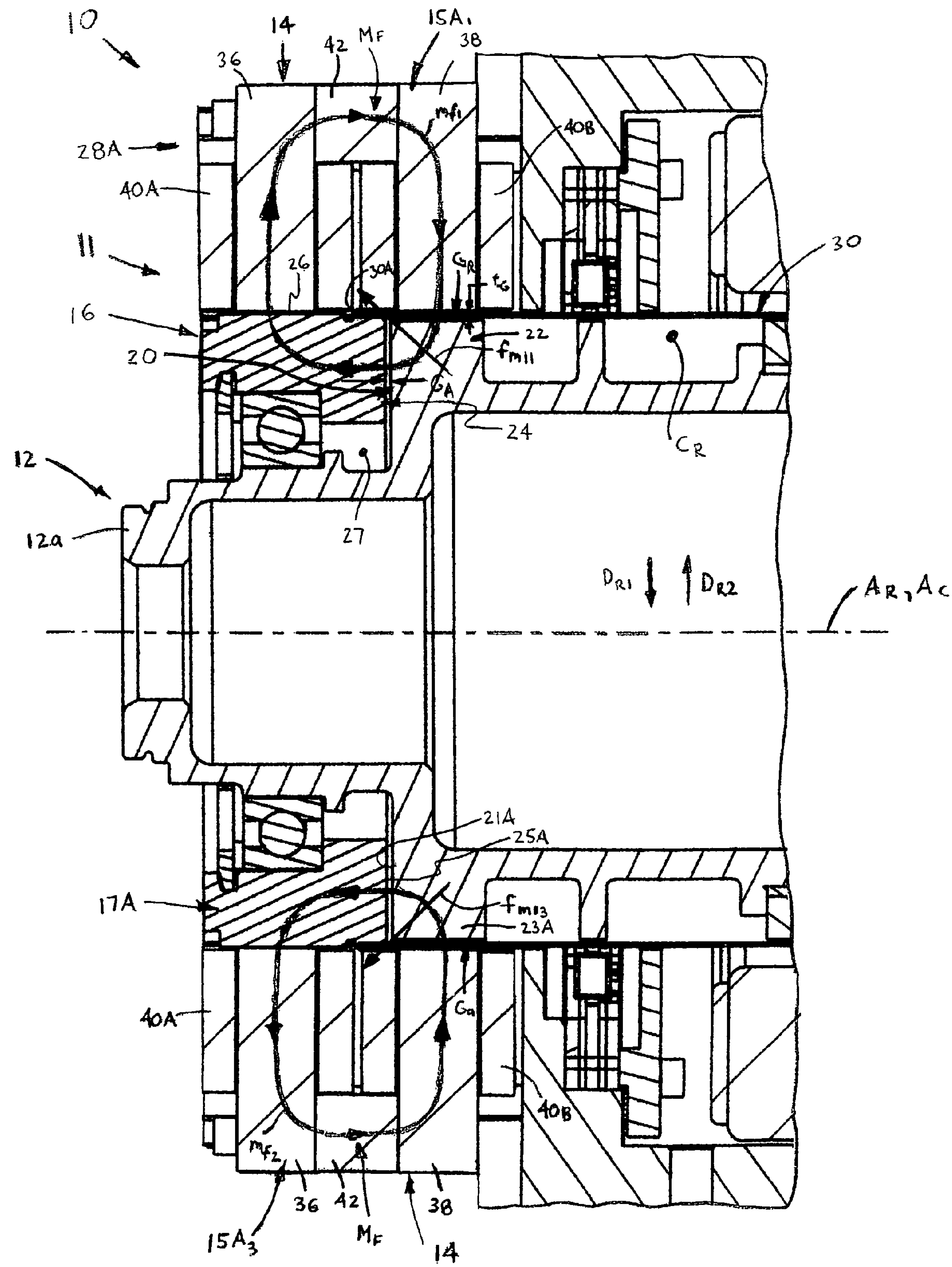
25A
25B
26
27
28A
28B
29
30
30A
30B
32
33
34A
34B
35
44
46
48
50
52
53A
53B
56
A_R, A_C
C_R
P_A, P_R
D_{R1}
D_{R2}
D_{A1}
D_{A2}

FIG. 2



10
14
42
M_F
$15A_1$
38
36
m_{f1}
28A
40B
40A
11
26
30A
G_R
t_G
30
16
22
f_{m11}
20
G_A
24
C_R
12
27
12a
D_{R1}
D_{R2}
A_R, A_C
21A
25A
17A
f_{m13}
23A
G_a
40A
40B
m_{f2}
36
42
38
$15A_3$
M_F
14

FIG. 3

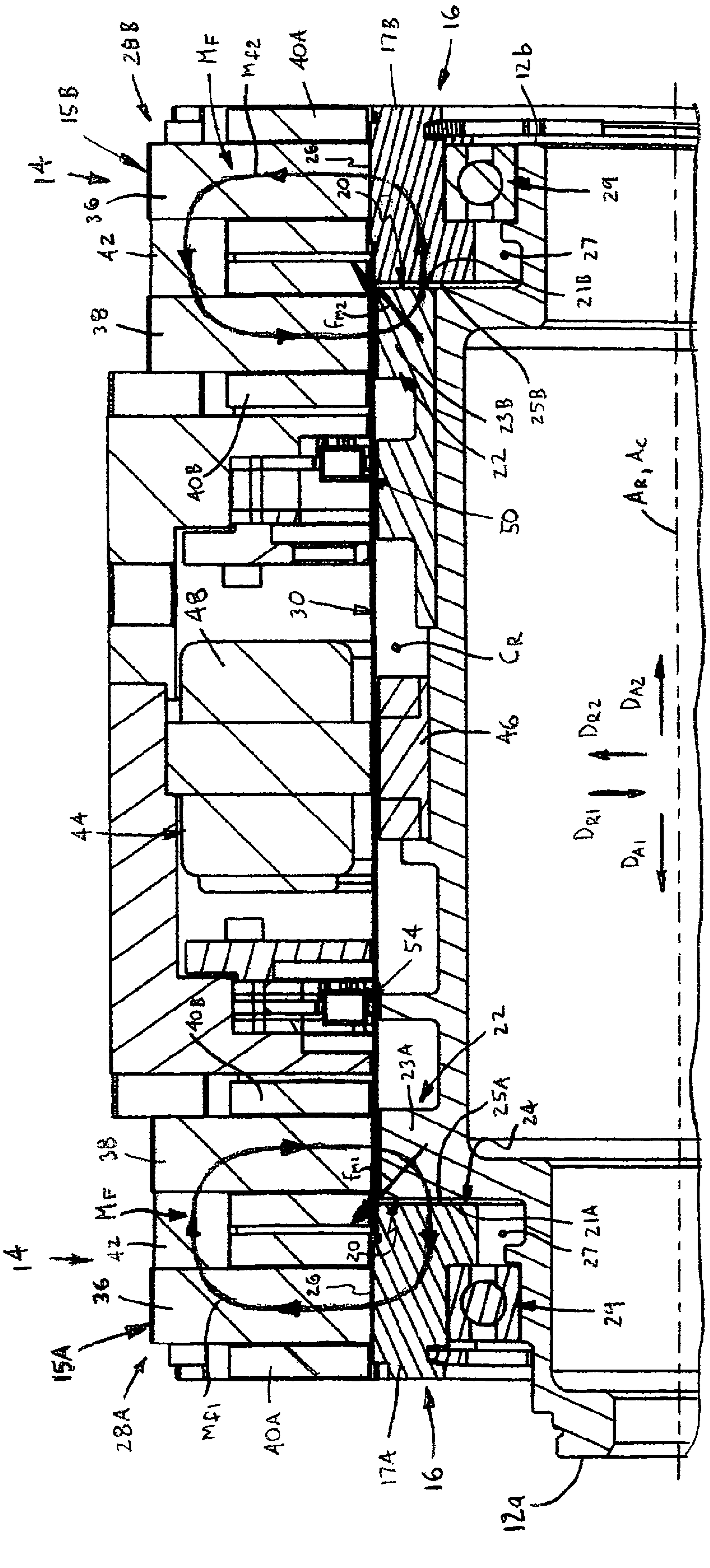


FIG. 4

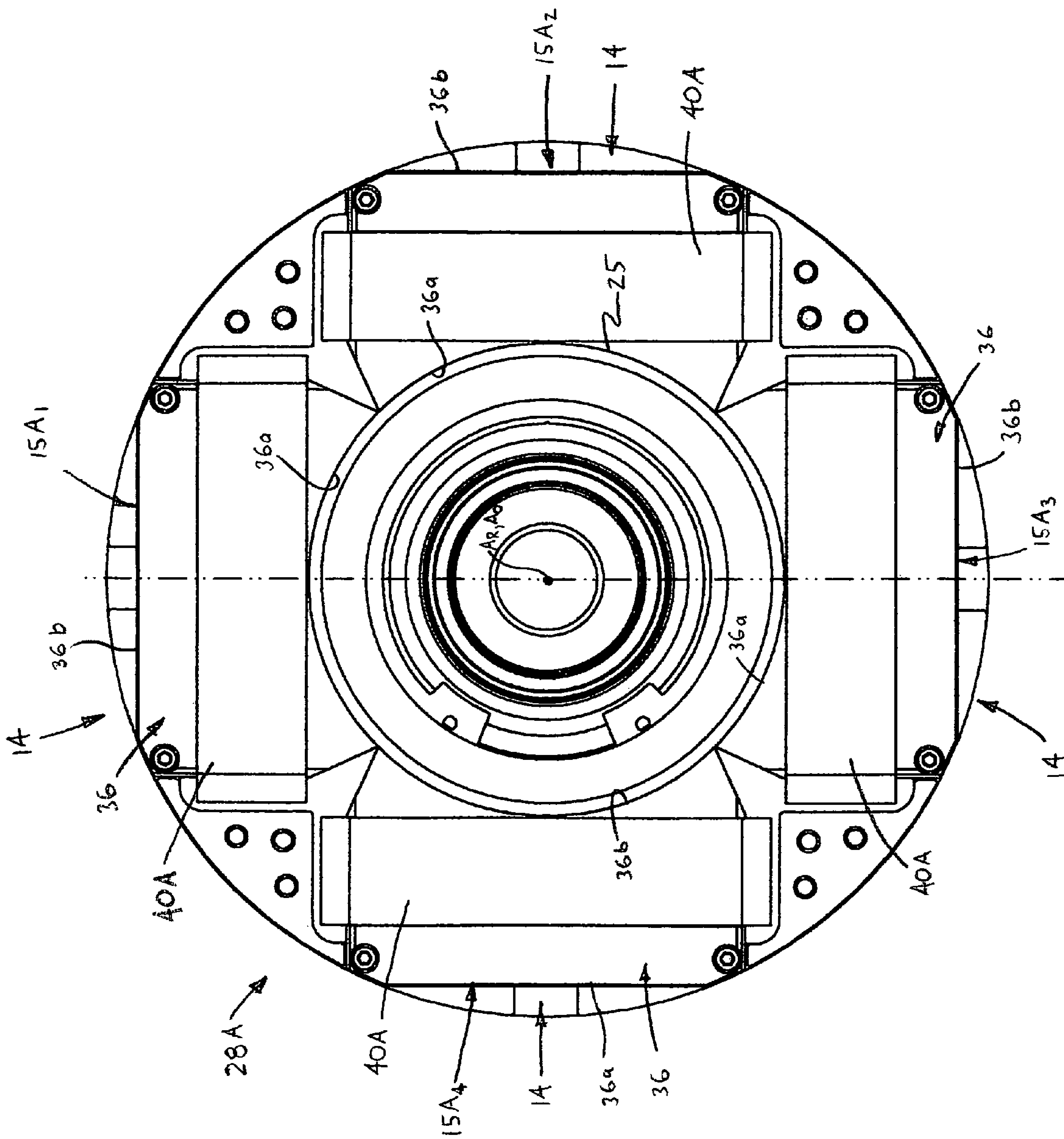


FIG. 5

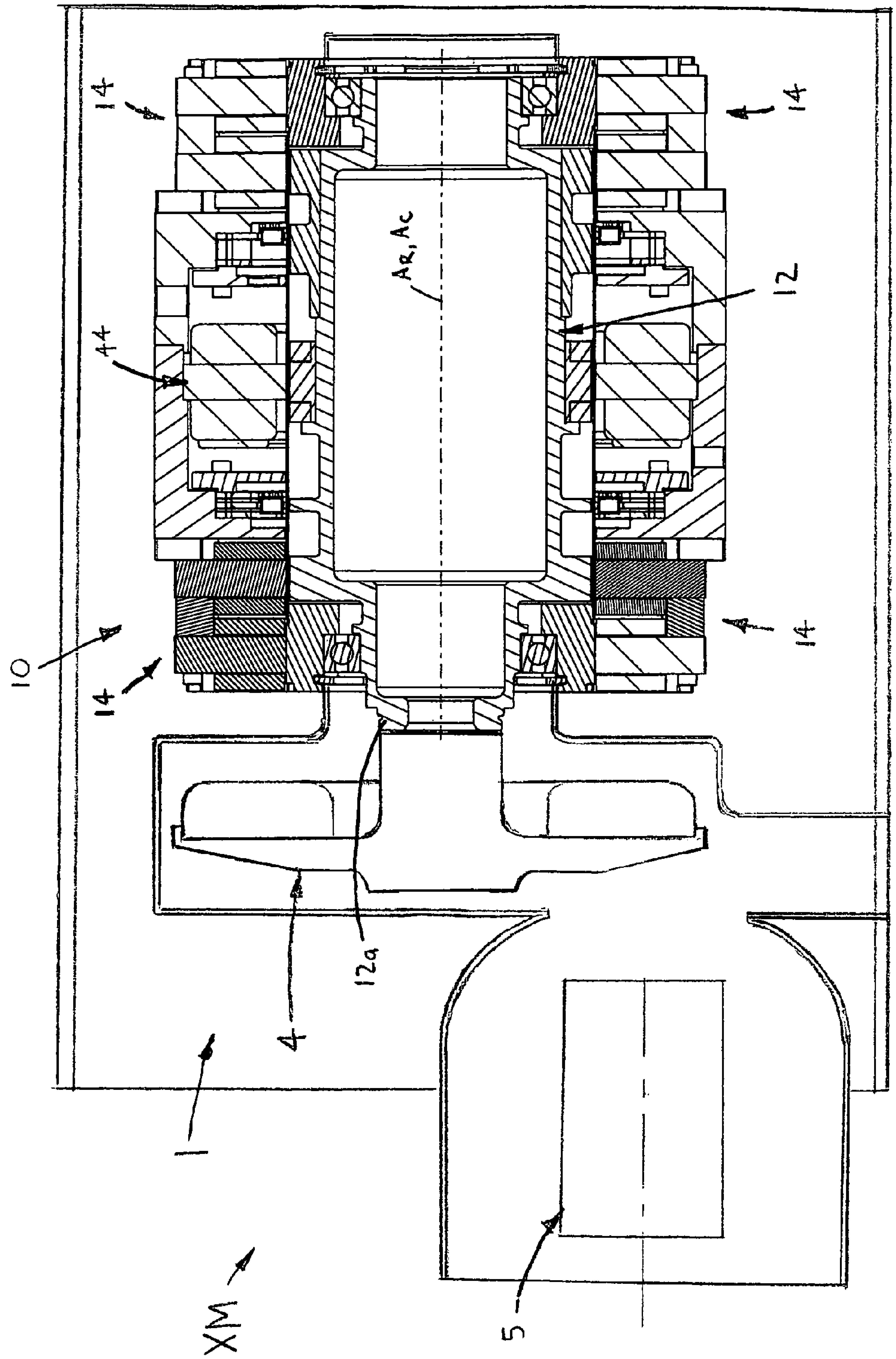


FIG. 6

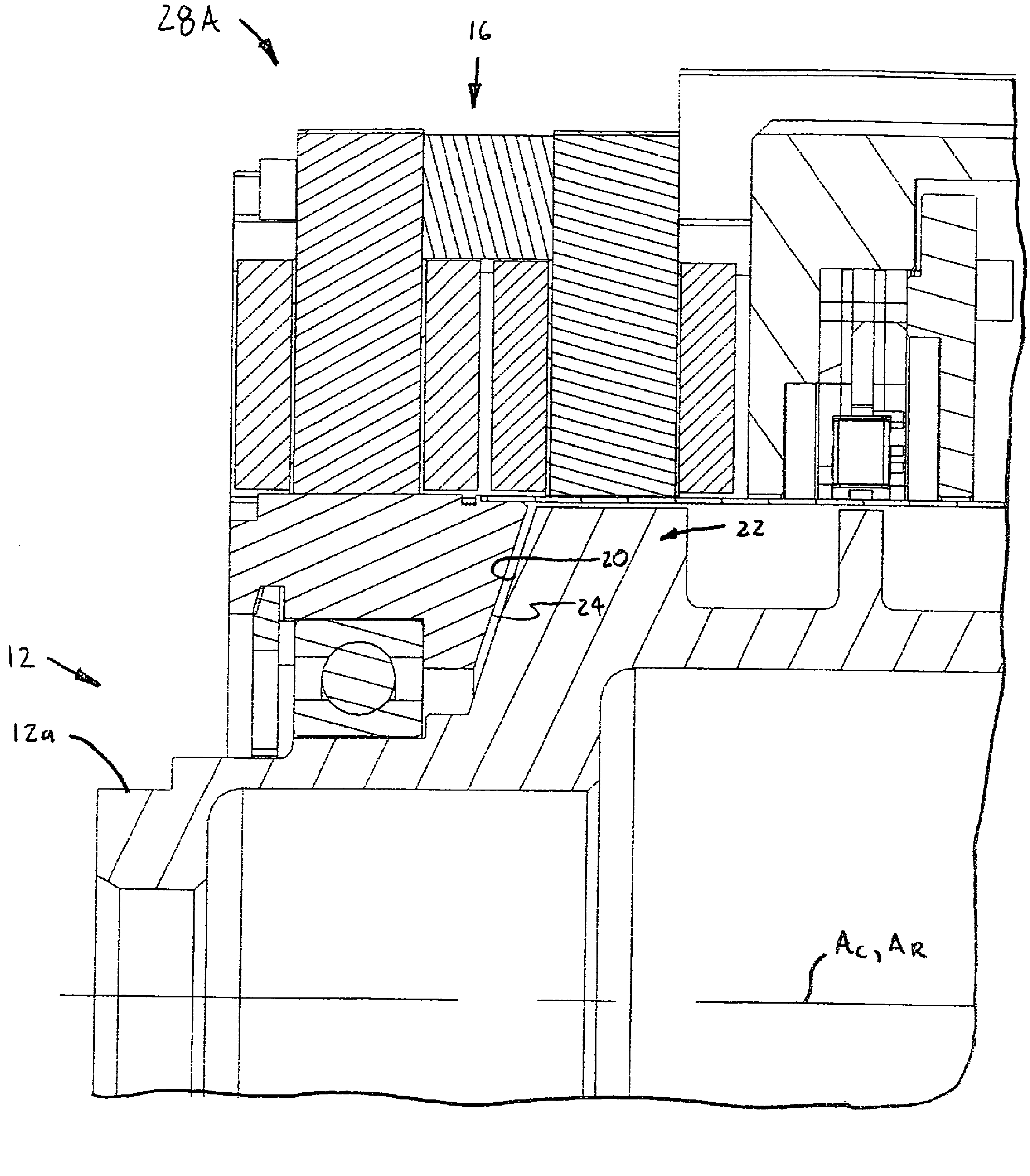


FIG. 7

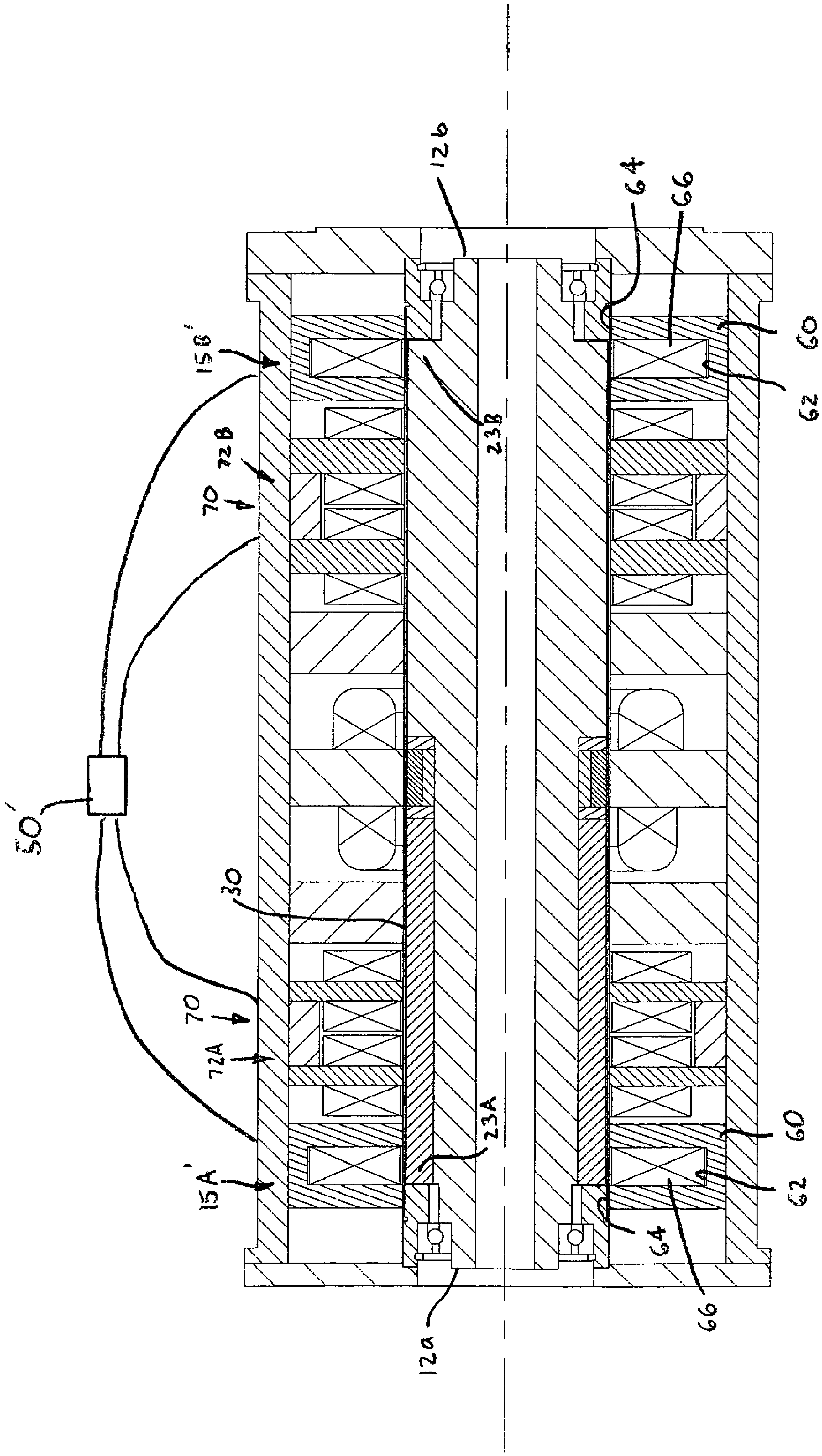


FIG. 8

MAGNETIC BEARING ASSEMBLY FOR ROTORS

The present invention relates to rotor assemblies, and more particularly to rotor assemblies supported by magnetic bearings.

Magnetic bearing assemblies for supporting rotors, such as the shaft of a compressor, X-ray anode shafts, etc., are generally known and typically include one or more electromagnets for exerting a force on the shaft. The electromagnet(s) may radially support or suspend the shaft, support radial or axial loading, and/or maintain the radial or axial position thereof, either as a primary bearing or as an auxiliary or back-up to another type of bearing (e.g., rolling element bearing, plain bearing, gas face, etc.). Typically, a magnetic bearing actuator only supports one type of loading, i.e., either radial or axial, such that a combination of different types of magnetic bearing actuators is generally required when both types of loading are a concern.

SUMMARY OF THE INVENTION

In one aspect, the present invention is a rotor assembly comprising a rotor having opposing first and second ends, a central axis extending generally between the two ends and generally parallel to a reference axis, and an at least generally radial surface, the rotor being rotatable about the central axis. At least one electromagnet is disposed proximal to and configured to exert magnetic force on a portion of the rotor. Further, a channeling member is disposed generally against the electromagnet and has a radial surface disposed generally adjacent to the rotor radial surface. As such, magnetic flux generated by the electromagnet extends generally radially between the electromagnet and the rotor portion and generally axially between the rotor portion and the channeling member so that the magnetic force biases the rotor both radially and axially with respect to the reference axis to maintain the rotor generally centered about the reference axis.

In another aspect, the present invention is a magnetic bearing assembly for a rotor assembly including a rotor having opposing first and second ends, a central axis extending generally between the two ends and generally parallel to a reference axis, and a radial surface, the rotor being rotatable about the central axis. The magnetic bearing assembly comprises at least one electromagnet disposed proximal to and configured to exert magnetic force on a portion of the rotor and a channeling member. The channeling member is disposed generally against the electromagnet and has a radial surface disposed generally adjacent to the rotor radial surface. As such, magnetic flux generated by the electromagnet extends generally radially between the electromagnet and the rotor portion and generally axially between the rotor portion and the channeling member so that the magnetic force biases the rotor both radially and axially with respect to the reference axis to maintain the rotor generally centered about the reference axis.

In a further aspect, the present invention is a rotor assembly comprising a rotor having opposing first and second ends, a central axis extending generally between the two ends and generally parallel to a reference axis, and first and second radial surfaces, the rotor being rotatable about the central axis. First and second electromagnets are spaced apart along the reference axis, the first electromagnet being disposed proximal to and is configured to exert magnetic force on a first portion of the rotor so as to bias the rotor first portion radially and axially with respect to the reference axis. The second electromagnet is disposed proximal to and is configured to exert magnetic force on a second portion of the rotor so as to

bias the rotor second portion both radially and axially with respect to the reference axis. Further, first and second generally annular channeling members are spaced apart along the reference axis, the first channeling member being disposed generally against the first electromagnet and has a radial surface disposed generally adjacent to the rotor first radial surface and the second channeling member is disposed generally against the second electromagnet and has a radial surface disposed generally adjacent to the rotor second radial surface. Furthermore, a generally cylindrical tubular housing has a first end disposed against the first channeling member and a second end disposed against the second channeling member, the housing and the channeling members defining a chamber, at least a portion of the rotor being disposed within the chamber.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

The foregoing summary, as well as the detailed description of the preferred embodiments of the present invention, will be better understood when read in conjunction with the appended drawings. For the purpose of illustrating the invention, there is shown in the drawings, which are diagrammatic, embodiments that are presently preferred. It should be understood, however, that the present invention is not limited to the precise arrangements and instrumentalities shown. In the drawings:

FIG. **1** is perspective view of a rotor assembly in accordance with the present invention;

FIG. **2** is an axial cross-sectional view through the rotor assembly;

FIG. **3** is a greatly enlarged view of a front portion of FIG. **2**;

FIG. **4** is an enlarged view of an upper portion of FIG. **2**;

FIG. **5** is a front plan view the rotor assembly;

FIG. **6** is an axial cross-sectional view of the rotor assembly incorporated into an X-ray tube assembly;

FIG. **7** is a greatly enlarged, broken-away axial cross-sectional view of an upper, front portion of the rotor assembly, showing alternative constructions of a rotor and a channeling member; and

FIG. **8** is an axial cross-sectional view of an alternative construction of the rotor assembly having separate radial actuators.

DETAILED DESCRIPTION OF THE INVENTION

Certain terminology is used in the following description for convenience only and is not limiting. The words "inner", "inwardly" and "outer", "outwardly" refer to directions toward and away from, respectively, a designated centerline or a geometric center of an element being described, the particular meaning being readily apparent from the context of the description. As used herein, the word "connected" is intended to include direct connections between two members without any other members interposed therebetween and indirect connections between members in which one or more other members are interposed therebetween. The terminology includes the words specifically mentioned above, derivatives thereof, and words of similar import.

Referring now to the drawings in detail, wherein like numbers are used to indicate like elements throughout, there is shown in FIGS. **1-8** a rotor assembly **10**, which in one embodiment is incorporated into an X-ray anode assembly **1** of an X-ray machine XM, as described below. The rotor assembly **10** basically comprises a rotor **12**, a magnetic bearing assembly **11** including at least one and preferably a plurality of electromagnets **14**, and at least one and preferably two channeling members **16**. The rotor **12** has opposing first and second ends **12***a*, **12***b*, a central axis A_C extending generally between the two ends **12***a*, **12***b* and generally parallel to a reference axis A_R, and one or more generally radially-extending or "radial" surfaces **20**, preferably first and second axially-spaced radial surfaces **21**A, **21**B facing in opposing axial directions. The rotor **12** is rotatable about the central axis A_C, which is preferably maintained substantially parallel with the reference axis A_R, such that the axes A_C, A_R are either collinear or radially offset, but the axes A_C, A_R may alternatively be skewed or intersecting. The at least one electromagnet **14** is disposed proximal to and is configured to exert a magnetic force f_{mn} on a generally proximal portion **22** of the rotor **12**.

Further, each of the one or two channeling members **16** is disposed generally against at least one electromagnet **14** and has an at least generally radial surface **24** disposed generally adjacent to a proximal rotor radial surface **20**, and preferably spaced a relatively short axial distance from the surface **20** so as to define an "axial" gap G_A (see FIG. **3**). Preferably, the radial surfaces **20**, **24** of the rotor **12** and the channeling member(s) **16**, respectively, are substantially radial or radially-extending as depicted in FIGS. **1-6** and **8**. However, the rotor **12** and the channeling member(s) **16** may alternatively be constructed such that the surfaces **20**, **24** are each also partly axially-extending, and thus only "generally" radially-extending or radial, as depicted in FIG. **7**.

With this structure, the magnetic flux M_F generated by each of the one or more electromagnets **14** extends generally radially between the electromagnet **14** and the proximal rotor portion **22** and generally axially between the rotor portion **22** and the proximal channeling member **16**. As such, the magnetic force f_{mn} generated by each electromagnet **14** biases the rotor **12** both radially and axially with respect to the reference axis A_R, with all of the electromagnets **14** being preferably arranged to maintain the rotor **12** generally centered about the reference axis A_R, i.e., so that the axes A_R, A_C are substantially parallel and either collinear or radially offset (or even skewed/intersecting), and at about a desired axial position P_A (FIG. **2**) with respect to the reference axis A_R. Thus, when operated by a control **50**, as described below, the one or more electromagnet(s) **14** provide a magnetic bearing assembly **11** that maintains the rotor **12** at a specific, desired axial and radial position P_A on the reference axis A_R, and preferably also supports or "levitates" the rotor **12** at the desired position P_A.

Referring now to FIGS. **2** and **4**, the rotor assembly **10** preferably includes first and second electromagnets **15**A, **15**B, respectively, spaced apart along the reference axis R_A and first and second channeling members **17**A, **17**B, respectively, also spaced apart along the axis R_A. By having at least two spaced-apart electromagnets **15**A, **15**B, the electromagnets **14** of the rotor assembly **10** are capable of biasing the rotor **12** in opposing directions D_{A1}, D_{A2} along the reference axis A_R, as described below. More specifically, one or more first electromagnets **15**A are each disposed proximal to and configured to exert magnetic force f_{M1} on a first portion **23**A of the rotor **14**, and are located at least generally proximal to the rotor first end **12***a*. Further, one or more second electromagnets **15**B are each disposed proximal to and configured to exert magnetic force f_{M2} on a second portion **23**B of the rotor **12**, and are located at least generally proximal to the rotor second end **12***b*. Further, the first channeling member **17**A is disposed generally against (i.e., either in contact with or separated by a minimal clearance) the one or more first or second electromagnets **15**A and has a generally radial surface **25**A disposed generally adjacent to, and preferably spaced a short axial distance from, a rotor first radial surface **21**A. In a similar manner, the second channeling member **17**B is disposed generally against the one or more second electromagnets **15**B and has a generally radial surface **25**B disposed generally adjacent to (and preferably slightly axially spaced from) a rotor second radial surface **21**B.

Referring particularly to FIG. **4**, with the above-described structure, magnetic flux m_{f1} generated by each first electromagnet **15**A extends generally radially between the electromagnet **15**A and the rotor first portion **23**A and generally axially between the rotor first portion **23**A and the first channeling member **17**A. Also, magnetic flux m_{f2} generated by each second electromagnet **15**B extends generally radially between the second electromagnet **15**B and the rotor second portion **23**B and generally axially between the rotor second portion **23**B and the second channeling member **17**B.

Preferably, electric current is adjustably supplied to each of the first and second electromagnets **15**A, **15**B, as determined by the control **50** as described below, such that the magnetic flux m_{F1}, m_{F2} of each electromagnet **15**A, **15**B extends or "flows" between the associated rotor portion **21**A, **21**B and the channeling member **17**A, **17**B so as to exert the magnetic forces f_{M1}, f_{M2} in opposing axial directions D_{A1}, D_{A2}, as shown in FIG. **4**. As is known to those skilled in the art of electromagnets, the magnitude of the force f_{mn} exerted by each electromagnet **14** on the rotor **12** is as determined by the magnitude of the current through the particular electromagnet **14** and the distance between the rotor **12** and the electromagnet **14**. Thus, when the magnitude of the force f_{m1}, f_{m2} exerted by the one or more electromagnets **15**A, **15**B is approximately equal, the forces f_{m1}, f_{m2} are offsetting (i.e., cancelling due to opposing directions) when the electromagnets **14** are "radially balanced" as described below, such that the rotor **12** is retained at a particular position on the reference axis A_R. However, when the control **50** determines that the rotor **12** should be displaced along the axis A_R so as to be repositioned at a desired axial position/location, the control **50** adjusts the current in either the first or second electromagnets **15**A, **15**B such that a net axial force is exerted on the rotor **12** to displace the rotor **12** in a desired axial direction D_{A1} or D_{A2}.

Although preferably including first and second axially spaced electromagnets **15**A, **15**B, most preferably two sets **28**A, **28**B thereof as described below, the rotor assembly **10** may alternatively include one or more electromagnets **14** at a single axial location and which exert magnetic force only on one portion **22** of the rotor **12**, in which case the rotor assembly **10** would only include a single channeling member **16**. Such an alternative rotor assembly **10** may also include another mechanical or electrical biasing means, such as one or more springs, permanent magnets, etc., to provide a counteracting bias or may function solely with the one or more electromagnets at the single location.

Referring to FIGS. **1-5**, the rotor assembly **10** preferably includes a first set **28**A of the first electromagnets **15**A and a second set **28**B of the second electromagnets **15**A, **15**B. Each electromagnet set **28**A, **28**B includes a plurality of electromagnets **15**A, **15**B, respectively, spaced circumferentially about the reference axis A_R. As such, each rotor portion **21**A, **21**B is "radially balanced" when both the current in each electromagnet **15**A, **15**B is substantially equal and the spacing between each rotor portion **21**A, **21**B and each electromagnet **15**A or **15**B of the associated set **28**A, **28**B is substantially equal. Preferably, each electromagnet set **28**A, **28**B includes four electromagnets **14**, such that the rotor assembly **10** includes a total of eight electromagnets **14**. More specifically, the first electromagnet set **28**A preferably includes four electromagnets **15**A_1, **15**A_2, **15**A_3, and **15**A_4 spaced apart in at least generally equal angular increments about the reference axis A_R, as indicated in FIG. **5**, and the second electromagnet set **28**A includes four similarly arranged electromagnets **15**B. Further, each one of the plurality of electromagnets **15**A, **15**B of each electromagnet set **28**A, **28**B is configured to exert magnetic force f_{M1n}, f_{M2n}, on the associated rotor portion **23**A, **23**B, specifically on a section of the particular rotor portion **23**A, **23**B that is proximal to the particular electromagnet **15**A, **15**B at any moment during angular rotation of the rotor **12**, as indicated in FIG. **3** for the first electromagnets **15**A_1 and **15**A_3.

Furthermore, the first and second channeling members **17**A, **17**B are preferably each disposed generally against (i.e., in contact with or separated by clearance) each one of the plurality of electromagnets **15**A, **15**B of the associated set of magnets **28**A, **28**B, respectively. More specifically, each channeling member **17**A, **17**B is preferably generally annular and has an outer circumferential surface **26** and a central bore **27**, and may be formed as a one-piece body (i.e., a ring) or an assembly of connected-together, generally arcuate segments. The channeling members **17**A, **17**B are each spaced radially inwardly from the associated electromagnets **15**A, **15**B such that each of the plurality of electromagnets **15**A, **15**B of the associated electromagnet set **28**A, **28**B is disposed against the channeling member outer circumferential surface **26**. Preferably, with annular channeling members **17**A, **17**B, the rotor **12** extends at least partially through each channeling member bore **27** and also through a separate auxiliary bearing **29** disposed in each channeling member **17**A, **17**B.

More specifically, each auxiliary bearing **29** is preferably disposed within the bore **27** of a separate one of the two channeling members **17**A, **17**B, such that the channeling members **17**A, **17**B each further function as a housing for the associated auxiliary bearing **29**. Further, the auxiliary bearings **29** are each disposed about, and spaced radially outwardly from, a separate section of the rotor **12**, such that the rotor **12** generally rotates within the static bearings **29** during normal operation of the rotor assembly **10**. Preferably, each auxiliary bearing **29** is a rolling element bearing, but may alternatively be a plain bearing and/or the bearings **29** may be disposed at any other locations on the rotor **12** (i.e., externally of the channeling members **17**A, **17**B).

Referring particularly to FIG. **3**, with one or more sets **28**A, **28**B of circumferentially-spaced electromagnets **14** as discussed above, when the magnitude of the radial component of the force generated by current through all of the electromagnets **15**A or **15**B of a particular set **28**A, **28**B, respectively, is approximately equal, the radial component of the force f_{m1n} or f_{m2n} generated by each electromagnet **14** is radially balancing or offsetting, such that the rotor **12** is retained at a particular radial position on the reference axis A_R. In other words, although subjected to separate or discrete forces f_{m1n} or f_{m2n} exerted by a plurality of electromagnets **14**, the rotor **12** is maintained at a particular radial position (i.e., centered on or offset from the axis A_R) when the magnitude of the radial component of each force f_{m1n} or f_{m2n} is generally equal due to the radial components of the separate forces being equal, but applied in opposing directions, such that net radial force exerted by all the magnets **15**A or **15**B of each electromagnet set **28**A, **28**B is substantially zero. This state is illustrated in FIG. **3** by electromagnets **15**A_1 and **15**A_3 of the first electromagnet set **28**A and preferably results in the rotor **12** being substantially supported or "levitated" by all the electromagnets **14** of the rotor assembly **10**. Further, in the desired "steady state" arrangement, the rotor **12** is maintained separated from each electromagnet **14** by a separate radial gap G_R, each radial gap G_R having a radial thickness t_G, as indicated in FIG. **3**. Specifically, when the rotor central axis A_C is retained generally collinear with the reference axis A_R, the radial gaps G_R have approximately equal thicknesses t_G, but the gap thicknesses t_G vary about the reference axis A_R when the central axis A_C is offset therefrom.

However, when the control **50** determines that the rotor **12** should be displaced radially with respect to the axis A_R so as to be repositioned at a desired radial position/location (e.g., centered on the axis A_R), the control **50** adjusts the current in one or more electromagnets **14** of a particular set **28**A, **28**B to be either greater than or lesser than the current in the other electromagnets **14** of the same set **28**A, **28**B. Thereby, a greater magnetic force is exerted on the section of the rotor portion **21**A or/and **21**B adjacent to the electromagnet(s) **15**A, **15**B having greater current, such that a net radial force is exerted on the rotor **12** to displace the rotor **12** in a desired radial direction D_{R1} or D_{R2}.

For example, if the control **50** increases current in one electromagnet **15**A of the first set **28**A and generally simultaneously in the axially aligned second electromagnet **15**B of the second set **28**B, the entire rotor **12** will displace radially in a direction D_{R1} or D_{R2} toward the particular first and second electromagnets **15**A, **15**B. However, if current is increased in a first electromagnet **15**A and generally simultaneously in a second electromagnet **15**B on an opposing side of the axis A_R, the two ends **12***a*, **12***b* of the rotor **12** displace in opposing radial directions, such that rotor **12** "tilts" back to the desired orientation (i.e., with the rotor central axis A_C collinear with the reference axis A_R). Further, in either of these cases, if one rotor portion **23**A, **23**B is located more proximal to the adjacent channeling member **17**A, **17**B in comparison with the other rotor portion **23**B, **23**A, the rotor **12** will also displace axially toward the more proximal channeling member **17**A, **17**B when the current increases due to a greater increase in the axial component of the exerted force f_{m1n} or f_{m2n}.

Although two sets **28**A, **28**B of circumferentially-spaced electromagnets **14** is presently preferred, the rotor assembly **10** may alternatively include only a single set of electromagnets **28**A or **28**B located generally proximal to one rotor end **12***a* or **12***b*, and may further include a mechanical or magnetic means of biasing the other rotor end **12***b*, **12***a* (e.g., spring, permanent magnet, etc.).

As best depicted in FIG. **2**, the rotor assembly **10** preferably further comprises a generally cylindrical tubular body **30** having a first end **30***a* coupled with the first channeling member **17**A and a second end **30***b* coupled with the second channeling member **17**B, such that body **30** and channeling members **17**A, **17**B form a housing **31**. More specifically, the tubular body **30** is preferably substantially circular and has a relatively slight wall thickness (i.e., is "thin-walled"). Further, the body **30** and the channeling members **17**A, **17**B define an interior "rotor" chamber C_R, at least a portion of the rotor **12** being disposed within the chamber C_R. With the one preferred embodiment of the rotor assembly **10** being an X-ray anode assembly **1**, the housing **30** and channeling members **17**A, **17**B are configured to substantially prevent gas flow between the interior chamber C_R and an exterior space S_E such that the chamber C_R is substantially evacuateable of gas. In other words, air can be evacuated from the rotor chamber C_R to form a partial vacuum, such that the housing **31** is a substantially sealed unit for containing at least a potion of the rotor **12** in an isolated environment. However, the sealed housing **31** may alternatively be utilized to contain a quantity of gas within the chamber C_R that has a pressure exceeding ambient pressure.

Furthermore, each end **30***a,* **30***b* of the tubular body **30** preferably extends about or "overlaps" a portion of the outer circumferential surface **26** of each annular member **17**A, **17**B, and is most preferably secured thereto by weldment material. However, the channeling members **16** and the tubular body **30** may alternatively be connected together, either fixedly or removably, by any other appropriate means (e.g., threaded fasteners, rivets, glue, press fit, etc.), the tubular body **30** may fit within a portion of each channeling member **17**A, **17**B, and/or the tubular body **30** and channeling members **16** may be connected by one or more separate components (e.g., spacer rings). As a further alternative, the channeling members **17**A, **17**B and the tubular body **30** may be provided as portions of a unitary or one-piece construction.

As best shown in FIG. **2**, the rotor **12** preferably includes a generally tubular body **32** with a central bore **35** and includes a radially-larger central section **33** and two radially-smaller end sections **34**A, **34**B. The rotor body central section **33** is sized to fit at least generally closely within the tubular body **30** and provides the end surfaces **21**A, **21**B and the rotor portions **23**A, **23**B interacting with the electromagnets **14**. Each rotor body end section **34**A, **34**B provides a separate one of the rotor ends **12***a,* **12***b,* respectively, and is disposed within a separate one of the annular channeling members **17**A, **17**B, respectively. Although the described rotor structure is presently preferred, the rotor **12** may be formed in any other appropriate manner, such as being substantially solid as opposed to tubular, having a substantially constant outside diameter as opposed to two radially inwardly-stepped end sections **33**A, **33**B, etc., and the present invention is in no manner limited to any particular rotor structure.

Referring now to FIGS. **1**, **3** and **5**, each electromagnet **14** preferably includes two core members **36**, **38** spaced apart generally along the reference axis A_R and two coils **40**A, **40**B. Each coil **40**A, **40**B is disposed circumferentially about a separate one of the core members **36**, **38**, respectively, and is connectable with a source of electric power (e.g., a battery, an electric outlet, etc.). As such, magnetic flux M_F extends in a generally circuitous path through the two core members **36**, **38**, which are preferably spaced by magnetically permeable channeling member **42** (as described below), the proximal rotor portion **23**A, **23**B and the associated channeling member **17**A, **17**A when current flows through the two coils **38***a,* **38**B.

More specifically, each electromagnet **14** is located with respect to the rotor **12** such that the associated rotor portion **23**A or **23**B is generally radially adjacent to one core member **38** and is spaced axially from the other core member **36**. As such, magnetic flux M_F extends at least generally radially between the one core member **38** and the adjacent rotor portion **22**, specifically through a section of the tubular body **30** disposed between the particular core member **38** and the rotor portion **22**, and extends generally axially, via the associated channeling member **17**A or **17**B, between the other core member **36** and the particular rotor portion **22**. Further, the rotor **12** has an outer circumferential surface **25** extending about each rotor portion **23**A, **23**B and each of the two core members **36**, **38** has inner radial end **36***a,* **38***a* and an outer radial end **36***b,* **38***b.* The inner end **38***a* of one the one core member **38** is radially adjacent to the rotor outer circumferential surface **25** and the inner end **36***a* of the other core member **36** is spaced axially from the rotor radial surface **20**. Furthermore, each electromagnet **14** also preferably further includes a magnetically permeable channeling member **42** disposed generally between the outer radial ends **36***b,* **38***a* of the two core members **36**, **38**, such that magnetic flux M_F passes between the core members **36**, **38** through the associated magnet channeling member **42**.

Although the above-described structure is presently preferred, the one or more electromagnets **14** may be formed in any other appropriate manner that is capable of enabling the rotor assembly **10** to function generally as described herein. Thus, the scope of the present invention includes all appropriate electromagnet types and electromagnet constructions for the electromagnet(s) **14** of the rotor assembly **10**.

Referring to FIGS. **2**, **4** and **6**, the rotor assembly **10** preferably further comprises a motor **44** configured to rotatably drive or displace the rotor **12** about the reference axis A_R, and thus with respect the electromagnets **14**, the two channeling members **16** and the housing body **30**. The motor **44** preferably includes a generally annular rotor **46** disposed or mounted to the rotor **12** and a generally annular stator **48** extending circumferentially about the rotor **46** and about a section of the tubular body **30** disposed between the rotor **46** and the stator **48**. Thereby, the motor **44** is able to drive the rotor **12** while the rotor **12** remains within the sealed chamber C_R. However, the rotor assembly **10** may be provided with any other appropriate mechanism or device for rotatably displacing the rotor **12**, such as for example a motor or engine coupled to an end **12***a* or **12***b* of the rotor **12** either directly or through a transmission device (e.g., gears, belts, coupler shafts, etc).

Referring particularly to FIG. **2**, as discussed above, the rotor assembly **10** preferably further comprises a control **50** configured to separately adjust electric current through each one of the plurality of electromagnets **15**A, **15**B so as to bias or displace the rotor **12**, particularly when the rotor **12** is spaced from a desired location/position. More specifically, to displace the rotor **12** radially, the control **50** adjusts current through at least one electromagnet **14** in one of the electromagnet sets **28**A, **28**B so that the force exerted on the rotor **12** by the at least one electromagnet **14** is greater than or lesser than the force generated by the other electromagnets **14** of the same set **28**A, **28**B. Additionally or alternatively, to displace the rotor **12** axially, the control **50** adjusts current in at least one electromagnet **15**A or **15**B of one set **28**A, **28**B of electromagnets **14** so that the force exerted on the rotor **12** by the electromagnet **15**A, **15**B is greater or lesser than the force exerted by the other set **28**B, **28**A of electromagnets **14**. Preferably, when it is desired to displace the rotor **12** axially, the control **50** is configured to adjust current through all of the electromagnets **15**A, **15**B of one set **28**A or **28**B of electromagnets **14** by a substantially equal amount and to be greater or lesser than the current in the electromagnets **15**B, **15**A of the other set of electromagnets **28**B, **28**A, so as to thereby prevent undesired radial displacement of the rotor **12**.

Further, the rotor assembly **10** preferably also comprises at least one sensor **52** coupled with the control **50** and configured to sense a radial position P_R of the rotor **12** with respect to the reference axis A_R and at least one sensor **52** coupled with the control **50** and configured to sense an axial position P_A of the rotor **12** with respect to the axis A_R. Also, the control **50** preferably further includes a value (i.e., stored in a memory, inputted, etc.) corresponding to a desired radial position P_R (i.e., centered on or radially spaced from the reference axis A_R) of the rotor **12** and a value corresponding to a desired axial position P_A of the rotor **12**. With such sensors **52**, the control **50** is further configured to compare the sensed radial and axial positions of the rotor **12** with desired axial and radial position values and to adjust current in the electromagnets **14** as necessary to reposition the rotor **12**.

That is, the control **50** adjusts current through at least one electromagnet **15**A, **15**B of at least one of the first and second sets of electromagnets **28**A, **28**B to displace the rotor **12** in a radial direction D_{R1}, D_{R2} when the control **50** determines a noncorrespondence between the sensed radial position and the desired radial position value V_R. Simultaneously or alternatively, the control **50** adjusts current through at least one electromagnet **15**A, **15**B of one of the first and second sets **28**A, **28**B of electromagnets **14** so as to displace the rotor **12** in an axial direction D_{A1}, D_{A2} when the control **50** determines a noncorrespondence between the sensed axial position and the desired axial position value V_A. It must be noted that such desired position values V_A, V_R may be "permanently" stored in a memory of the control **50** or may vary in accordance with a control program or external input. Further, the rotor assembly **10** most preferably includes a first sensor assembly **53**A configured to sense both radial and axial position of the rotor **12** and a second sensor assembly **53**A configured to sense both rotor radial position and rotational speed of the rotor **12**. However, as is readily apparent to one skilled in the art of sensors and magnetic bearings, there are many possible arrangements of sensors for determining the radial and axial position, and rotational speed, of the rotor **12**, and the scope of the present invention is in no manner limited to any particular sensor structure or arrangement.

Referring particularly to FIG. **6**, in the preferred application of an X-ray anode assembly **1** for an X-ray machine XM, the rotor assembly **10** is preferably configured to receive an anode, as discussed above, and the anode assembly **1** further comprises an X-ray anode **4** mounted to one end **12***a* of the rotor **12**. As the motor **44** rotatably drives the rotor **12**, the anode **4** is angularly displaced with respect to an X-ray cathode **5**. As X-ray machines are generally known, a detailed description of the anode **4**, cathode **5** and other components of such an X-ray machine are beyond the scope of the present disclosure.

However, the benefits of the present rotor assembly **10** to such an X-ray machine XM must be noted. Specifically, by having the two annular channeling members **16** located with respect to opposing radial end surfaces **20** of the rotor **12** and radially inwardly of the electromagnets **14**, the electromagnets **14** are capable of biasing the rotor **12** both radially and axially due to the above-described path of the magnetic flux M_F through the portion(s) **22** of the rotor **12** and the channeling members **16**. Such a magnetic actuator structure eliminates the need for one or more radially-outwardly extending rotor flanges or angled rotor sections that would otherwise be required in order to provide an axial bias on the rotor **12**, which permits the rotor **12** to have a substantially circular cylindrical or tubular shape that is disposeable within the circular cylindrical tubular body **30**. Not only is such a straight-walled tubular body **30** relatively simple and cost effective to manufacture in comparison to the housings required to encapsulate a rotor with flanges or with angled sections (e.g., a housing with conical sections), a sealable housing **31** is readily and relatively inexpensively formed by attaching the ends **30***a*, **30***b* of the tubular body **30** to the preferred pair of channeling members **16**. These and other benefits will be readily apparent to those skilled in the art of magnetic bearings and devices incorporating such bearings.

Furthermore, it must also be noted that the utilization of the rotor assembly **10** in an X-ray anode assembly **1** is only one presently preferred application of the rotor assembly **10**. As such, the rotor assembly **10** may be used in any other appropriate application, particularly applications in which a sealed environment is desirable, and the scope of the present invention is in no manner limited to any particular application of the rotor assembly **10**.

Referring particularly to FIG. **8**, an alternative construction of the rotor assembly **10** is generally similar to the preferred construction described in detail above, but with the following differences. Instead of a plurality of separate first and second magnets **15**A, **15**B adjacent to each rotor portion **23**A, **23**B, the alternative construction includes only one first electromagnet **15**A' and one second electromagnet **15**B'. Each electromagnet **15**A', **15**B' includes an annular core member **60** extending circumferentially about the rotor **12**, and preferably externally about the tubular body **30**, with an annular groove **62** extending radially outwardly from an inner circumferential surface **64**, and an annular coil **66** disposed within the groove **62**. With this structure, each electromagnet **15**A', **15**B' exerts magnetic force about the entire circumference of the associated rotor portion **23**A, **23**B, such that radial components of the force exerted about the circumference are cancelling, and thus the electromagnets **15**A', **15**B' each only exert a net axial biasing force, when the rotor **12** is substantially centered within the electromagnets **15**A', **15**B'. As such, the alternative construction of the rotor assembly **10** preferably includes separate radial magnetic bearing actuators **70**, most preferably two sets of electromagnets **72**A, **72**B constructed substantially similarly to the first and second electromagnet sets **28**A, **28**B as described in detail above, except for being spaced axially inwardly from the rotor portions **23**A, **23**B. In use, the control **50'** adjusts current through the first and second electromagnets **15**A', **15**B' to adjust the axial position of the rotor **12** and/or adjusts current through the electromagnets **70**A, **70**B to adjust the radial position of the rotor **12**.

It will be appreciated by those skilled in the art that changes could be made to the embodiments described above without departing from the broad inventive concept thereof. It is understood, therefore, that this invention is not limited to the particular embodiments disclosed, but it is intended to cover modifications within the spirit and scope of the present invention as generally defined in the appended claims.

We claim:

1. A rotor assembly comprising:

a rotor having opposing first and second ends, a central axis extending generally between the two ends, the central axis being one of collinear with and generally parallel to a reference axis, and a radial surface, the rotor being rotatable about the central axis;

at least one electromagnet disposed proximal to and configured to exert magnetic force on a portion of the rotor; and

a channeling member disposed generally adjacent to the electromagnet and having a radial surface disposed generally adjacent to the rotor radial surface such that magnetic flux generated by the electromagnet extends generally radially between the electromagnet and the rotor portion and generally axially between the rotor portion and the channeling member so that the magnetic force biases the rotor both radially and axially with respect to the reference axis to maintain the rotor at a desired position with respect to the reference axis;

wherein the at least one electromagnet includes two core members spaced apart generally along the reference axis and two coils, each coil being disposed circumferentially about the core member and connectable with a source of electric power such that magnetic flux extends in a generally circuitous path through the two core members, the rotor portion and the channeling member when current flows through the two coils.

2. The rotor assembly as recited in claim **1** wherein the at least one electromagnet includes a plurality of electromagnets spaced circumferentially about the reference axis, each one of the plurality of electromagnets being configured to exert magnetic force on the rotor portion, the channeling member being disposed generally against each one of the plurality of electromagnets.

3. The rotor assembly as recited in claim **2** wherein the channeling member is generally annular and has an outer circumferential surface, each of the plurality of magnets being disposed generally against the channeling member outer circumferential surface.

4. The rotor assembly as recited in claim **3** wherein the channeling member includes one of a generally annular body and a plurality of connected segments.

5. The rotor assembly as recited in claim **2** further comprising a control configured to separately adjust electric current through each one of the plurality of electromagnets.

6. The rotor assembly as recited in claim **5** wherein the rotor is displaceable in a radial direction with respect to the reference axis when the control adjusts current through at least one of the plurality of electromagnets such that the force exerted by the at least one electromagnet on the rotor portion is one of greater than and lesser than the force exerted by at least one of the other electromagnets on the rotor portion.

7. The rotor assembly as recited in claim **1** wherein:

the at least one electromagnet is a first electromagnet, the channeling member is a first channeling member, the rotor portion is a first rotor portion, and the rotor radial surface is a first radial surface, the rotor further including a second surface section spaced axially from the first surface section; and

the rotor assembly further comprises a second electromagnet spaced axially from the first electromagnet and a second channeling member spaced axially from the first channeling member and disposed against the second electromagnet, the second electromagnet being configured to exert magnetic force on a second portion of the rotor, the second channeling member having a radial surface section disposed generally adjacent to the rotor second radial surface section such that magnetic flux generated by the second electromagnet extends generally radially between the second electromagnet and the other rotor portion and generally axially between the rotor portion and the channeling member so that the magnetic force exerted by the second electromagnet biases the rotor both radially and axially with respect to the reference axis.

8. The rotor assembly as recited in claim **1** wherein the channeling member is generally annular, is spaced radially inwardly from the electromagnet assembly, and has a central bore, the rotor extending at least partially through the bore.

9. The rotor assembly as recited in claim **8** further comprising an auxiliary bearing disposed within the channeling member and about the rotor, the auxiliary bearing being configured to at least rotatably support the rotor.

10. The rotor assembly as recited in claim **1** wherein the at least one electromagnet is located with respect to the rotor such that the rotor portion is generally radially adjacent to one of the two core members of the electromagnet and is spaced axially from the other one of the core members such that magnetic flux extends at least generally radially between the one core member and the rotor portion and extends generally axially between the other core member and the rotor portion.

11. The rotor assembly as recited in claim **10** wherein the rotor has an outer circumferential surface extending about the rotor portion, each of the two core members has inner and outer radial ends, the inner end of one of the two core members being radially adjacent to the rotor outer circumferential surface and the inner end of the other one of the core members is spaced axially from the rotor radial surface.

12. A magnetic bearing assembly for a rotor assembly, the rotor assembly including a rotor having opposing first and second ends, a central axis extending generally between the two ends and generally parallel to a reference axis, and a radial surface, the rotor being rotatable about the central axis, the magnetic bearing assembly comprising:

at least one electromagnet disposed proximal to and configured to exert magnetic force on a portion of the rotor;

a channeling member disposed generally against the electromagnet and having a radial surface disposed generally adjacent to the rotor radial surface such that magnetic flux generated by the electromagnet extends generally radially between the electromagnet and the rotor portion and generally axially between the rotor portion and the channeling member so that the magnetic force biases the rotor both radially and axially with respect to the reference axis to maintain the rotor generally centered about the reference axis, wherein the channeling member is generally annular, is disposed radially inwardly from the at least one electromagnet, and has a central bore configured to receive the rotor at least partially therein; and

an auxiliary bearing disposed within the channeling member and configured to surround the rotor so as to at least rotatably support the rotor.

13. A rotor assembly comprising:

a rotor having opposing first and second ends, a central axis extending generally between the two ends and generally parallel to a reference axis, and first and second radial surfaces, the rotor being rotatable about the central axis;

first and second electromagnets spaced apart along the reference axis, the first electromagnet being disposed proximal to and configured to exert magnetic force on a first portion of the rotor so as to bias the rotor first portion radially and axially with respect to the reference axis, the second electromagnet being disposed proximal to and configured to exert magnetic force on a second portion of the rotor so as to bias the rotor second portion both radially and axially with respect to the reference axis;

first and second generally annular channeling members spaced apart along the reference axis, the first channeling member being disposed generally against the first electromagnet and having a radial surface disposed generally adjacent to the rotor first radial surface and the second channeling member being disposed generally against the second electromagnet and having a radial surface disposed generally adjacent to the rotor second radial surface; and

a generally cylindrical tubular housing having a first end disposed against the first channeling member and a second end disposed against the second channeling member, the housing and the channeling members defining at least a portion of a sealable chamber, at least a portion of the rotor being disposed within the sealable chamber, and the first and second electromagnets being disposed radially outward of the tubular housing and exterior to the sealable chamber.

14. The rotor assembly according to claim **13**, wherein the first channeling member is immovably connected to the first end of the tubular housing and the second channeling member is immovably connected to the second end of the tubular housing.

15. The rotor assembly according to claim **14**, wherein:

the first and second channeling member are each at least generally annular and each have an outer circumferential surface and

at least a portion of the tubular housing radially overlaps the outer circumferential surface of each of the first and second channeling members.

16. The rotor assembly according to claim **14**, wherein:

the first and second channeling members each have a radial thickness that is greater than a radial thickness of the tubular housing and

at least one core member of each of the first and second electromagnets is separate from, and disposed radially outwardly of, the first and second channeling members, respectively.

17. The rotor assembly as recited in claim **13** further comprising a motor configured to rotatably drive the rotor about the rotor axis and including:

a generally annular rotor disposed on or mounted to the rotor and

a generally annular stator extending circumferentially about the rotor and about a section of the tubular body that is disposed between the rotor and the stator.

18. A rotor assembly comprising:

a rotor having opposing first and second ends, a central axis extending generally between the two ends, the central axis being one of collinear with and generally parallel to a reference axis, and a first radial surface axially spaced from a second radial surface, the rotor being rotatable about the central axis;

a first set of electromagnets disposed proximal to and configured to exert magnetic force on a first portion of the rotor,

a second set of electromagnets disposed proximal to and configured to exert magnetic force on a second portion of the rotor, each of the first and second sets of electromagnets including a plurality of electromagnets spaced circumferentially about the reference axis, each one of the plurality of electromagnets being configured to exert magnetic force on the respective first and second rotor portions;

a first channeling member disposed generally adjacent to, and against each one of the plurality of electromagnets of, the first set of electromagnets and having a first radial surface disposed generally adjacent to the rotor first radial surface such that magnetic flux generated by the first set of electromagnets extends generally radially between the first set of electromagnets and the first rotor portion and generally axially between the first rotor portion and the first channeling member so that the magnetic force biases the rotor both radially and axially with respect to the reference axis to maintain the rotor at a desired position with respect to the reference axis;

a second channeling member disposed generally adjacent to, and against each one of the plurality of electromagnets of, the second set of electromagnets and having a second radial surface disposed generally adjacent to the rotor second radial surface such that magnetic flux generated by the second set of electromagnets extends generally radially between the second set of electromagnets and the second rotor portion and generally axially between the second rotor portion and the second channeling member so that the magnetic force biases the rotor both radially and axially with respect to the reference axis to maintain the rotor at a desired position with respect to the reference axis; and

a control configured to separately adjust electric current through each of the plurality of electromagnets of each of the first and second sets of electromagnets such that the rotor is displaceable in an axial direction with respect to the reference axis when the control adjusts current through at least one electromagnet of one of the first and second sets of electromagnets such that the force exerted on the rotor by the at least one electromagnet is either greater than or lesser than the force exerted on the rotor by each electromagnet of the other one of the first and second sets of electromagnets.

19. The rotor assembly as recited in claim **18** wherein:

the control is configured to adjust current through all of the electromagnets of one of the first and second sets of electromagnets such that the force exerted on the rotor by each electromagnet is substantially equal to the force exerted on the rotor by each one of the other electromagnets of the set and is either greater than or lesser than the force exerted on the rotor by the electromagnets of the other one of the first and second sets of electromagnets so as to displace the rotor generally along the axis; and

the control is configured to adjust current through one of the electromagnets of at least one of the first and second sets of electromagnets such that the force exerted on the rotor by the one electromagnet is either greater than or lesser than the force exerted on the rotor by each one of the other electromagnets of the at least one set of electromagnets so as to displace the rotor generally radially with respect to the rotor axis.

20. The rotor assembly as recited in claim **19** further comprising a sensor coupled with the control and configured to sense at least one of an axial position of the rotor with respect to the reference axis and a radial position of the rotor with respect to the reference axis.

21. The rotor assembly as recited in claim **20** wherein:

the control includes a value corresponding to a desired axial position of the rotor and a value corresponding to a desired radial position of the rotor;

the control is further configured to compare a sensed axial position of the rotor with the desired axial position value and to adjust the current through at least one electromagnet of one of the first and second sets of electromagnets to displace the rotor in an axial direction when the control determines a non-correspondence between the sensed axial position and the desired axial position value; and

the control is further configured to compare a sensed radial position of the rotor with the desired radial position value and to adjust the current through at least one electromagnet of at least one of the first and second sets of electromagnets so as to displace the rotor in a radial direction when the control determines a non-correspondence between the sensed radial position and the desired radial position value.

22. The rotor assembly as recited in claim **18** wherein each of the first and second channeling members is generally annular and the rotor assembly further comprises a generally cylindrical tubular housing extending generally along the rotor axis and having a first end disposed against the first channeling member and a second end disposed against the second channeling member, the housing and the channeling members defining an interior chamber, the rotor being at least partially disposed within the interior chamber.

23. The rotor assembly as recited in claim **22** wherein the housing and channeling members are configured to at least substantially prevent gas flow between the interior chamber and an exterior space.

24. The rotor assembly as recited in claim **23** further comprising an X-ray anode coupled with one of the first and second ends of the rotor.

25. The rotor assembly as recited in claim **18** wherein each of the first and second sets of electromagnets includes two core members spaced apart generally along the reference axis and two coils, each coil being disposed circumferentially about the core member and connectable with a source of electric power such that magnetic flux extends in a generally circuitous path through the two core members, the rotor portion and the channeling member when current flows through the two coils.

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